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THE IMPORTANT EPOCHS IN THE DEVELOPMENT OF ASTRONOMY.

By R. T. Crawford.

When one stands in awe and admiration before the Woolworth Building in New York, the Campanile of Venice, or that of the University of California at Berkeley, some massive bridge with its network of girders, the Milan Cathedral, or any other wonderful work of man, rarely does he consider the separate and distinct processes that contribute to its construction. It is the finished product that receives the words of praise and commendation. The foundations and other parts out of sight are almost completely neglected. The question "Who was the architect?" is nearly always asked; "Who was the engineer?" is seldom heard. It is quite right that we should praise and admire the designer, but we should give due meed of praise and admiration to the engineer who figures the stresses and strains of the various members of the edifice and designs the foundations, without whose genius the architect's conception could not come to realization. Nor should we stop here, but reserve some of our thoughts of glorification for those architects, engineers, physicists, chemists, and mathematicians who have gone before, who have contributed their bits to improve their arts and sciences, step by step, age after age, until now it has become possible to erect a Woolworth Building; an impossibility a few short decades ago.

The completed edifice cannot be set down at once for the world to admire. It must be built up patiently, stone by stone, and must rest upon a solid foundation. It is with this idea in mind that I address you this evening. In the first series of the Adolfo Stahl Lectures you were presented with some aspects of astronomy of the present time, the finished edifice so to speak (altho no astronomical work is ever finished). In this, the first of the second series of the Adolfo Stahl Lectures, an attempt will be made to show you the various stepping stones that have been laid by the past masters of the science by which alone it has been possible to climb to the great heights attained by the astronomers of today.

In the brief time allotted for a single lecture it is impossible to tell the whole story, so I shall confine my remarks to the most important epochs in the development of astronomy, the oldest of the sciences.

In the earliest times the notions concerning the form of the Earth were as numerous and varied as there were peoples. About the 6th century B. C. Pythagoras and his followers taught that the Earth was spherical and a first advance seems to have been made. Many people have the erroneous idea that it was not known that the Earth is spherical until Magellan proved it by circumnavigating the globe.

The first determination of the distance from the Earth to the Sun was made by Aristarchus, 3rd century B. C. This determination was highly ingenious; correct geometrically but yielding a very inaccurate result. This problem is so difficult, however, that no good determination was made until the time of Cassini in the 17th century; so, great credit is due Aristarchus for any determination at this early date.

To Eratosthenes, 2nd century B. C., is due the first measurement of the size of the Earth. His method is practically that used today. Our determinations are better only because we can make more accurate observations and measurements than he could. (Here the lecturer explained briefly the method of Eratosthenes and showed a picture of "Eratosthenes' Well.")

The greatest astronomer of antiquity was undoubtedly Hipparchus, sometimes called the "Father of Astronomy," who flourished about the middle of the 2nd century B. C. To him we credit, among other things, the invention of trigonometry, the first star catalog of reasonable accuracy, the discovery of the precession of the equinoxes, and, above all else, the introduction of the truly scientific method of observation and investigation.

The first epoch in the development of astronomy may be said to have been brought to a close upon the appearance of Ptolemy's *Almagest*, the first great astronomical classic. Ptolemy lived in the 2nd century A. D. He does not seem to have contributed much original work to the science, but he rendered an inestimable service by bringing together in his monumental work, and thus preserving for us, nearly all that had been done by those who had preceded him.

The *Almagest* is noted principally for Ptolemy's exposition of the geocentric theory of the solar system, the theory that the Earth is the center of the system and that all of the other bodies, including the Sun, revolve about it in a system of circles or epicycles. He sets forth the arguments pro and con in the controversy between the geocentric and the heliocentric theories, and then, perhaps influenced by the great weight of Aristotle's opinion, rejects the heliocentric theory and adopts the geocentric.

Following the time of Ptolemy learning seems to have gone into nearly total eclipse during that period of about 14 centuries known as the Dark Ages. Many reasons have been assigned for the decline of learning in this period, but one of the principal causes is often overlooked. This is the powerful influence of the authority of Aristotle. Great as Aristotle may have been as a philosopher, as a scientist he was a failure. This is due to the fact that the tenets he set forth rested wholly upon thought analysis and were untested by actual experiment, a wholly unscientific method of procedure.

During this period it was considered that Aristotle had done all of the world's thinking, so that there was no further need of thinking. His influence was so great that no one dared to question any of his dicta. If one, perchance, was so hardy as to attempt it he was probably immediately silenced by some caustic question such as "Do you think you know more than Aristotle?" No one seems to have dared to think. No wonder the people were in the Dark Ages! It has been well said that Aristotle did more to retard the progress of the world, at least of the scientific world, than any other one man. How the Dark Ages came to an end will be related presently. In the meantime we come to the next important epoch in the development of astronomy.

At the end of the 15th century came Copernicus, who gave us the second great astronomical classic, the *De Revolutionibus Orbium Celestium.* In this Copernicus discussed the pros and cons of the two theories of the arrangement of the solar system as Ptolemy did; but came to a different conclusion. Copernicus held the heliocentric theory to be the true one, that is, that the Sun is the center of the solar system and that all of the planets, of which the Earth is one, revolved about the Sun.

As can readily be imagined this doctrine did not find ready acceptance. For many centuries the old geocentric idea had held sway and was not to be overthrown easily. It was about half a century later that the observations and teachings of Galileo gave the final push to the tottering geocentric theory and it fell.

From the middle of the sixteenth century to the middle of the seventeenth we find three epoch making names in astronomy, Tycho Brahé, Kepler, and Galileo. The latter two were contemporaneous following immediately after Tycho.

Beginning at this time we find a revival in observational work. This was carried on partly in Cassel, where we find the first observatory built with a revolving dome and the first use of a clock to record time observations. But the principal observational work then was done by Tycho at Hveen. He recognized the need of more accurate positions of the Sun, Moon, planets and stars than were available. Tycho, therefore, erected an elaborate observatory, and equipped it with as fine instruments as were then possible. While he made no startling discovery, he amassed a store of very accurate observations, especially of the planets, which were destined soon to play a very important role in the development of astronomy.

Tycho's valuable observations fortunately fell into the hands of Kepler, who mined thru them with remarkable patience and perseverance. Up to this time the positions of the planets had been predicted on the assumption that they moved in circles or combination of circles. But Kepler was soon able to show from Tycho's accurate observations that they could not move in such a way. He then set about to discover the true paths. After much trying and guessing he at last found that their motion could be represented accurately by ascribing the ellipse as the true path with the Sun situated at one focus of the ellipse. We have here the first departure from the old idea of motion in a circle.

Then Kepler reasoned, that as a planet is at varying distances from the Sun on account of moving in an ellipse, it probably would move with a variable velocity. Again he started his trying and guessing and finally hit upon his second wonderful law, namely, that a planet moves in such a way that the line joining the Sun and the planet describes equal areas in equal intervals of time.

Once more his active brain got to work and he began to consider the fact that as the various planets are at different distances from the Sun there is probably some relation between the distances and the time of revolution of the various planets about the Sun. If one planet is twice as far from the Sun as another, will it take twice as long to go once completely around the Sun? He soon saw that no such simple relation held true. So again he started his trying and guessing and finally arrived at his wonderful Harmonic Law, which states that the squares of the periods (expressed in years) are equal to the cubes of the mean distances from the Sun (the Earth's distance being taken as unity.)

You have probably gathered from all this that Kepler was the world's champion guesser; and he probably was. Even so he could not have arrived at these three wonderful laws had he not had his material systematically arranged. We are told that he chose his second wife after investigations most methodical. He put down on cards the points of merit of each one of nearly a dozen maidens, and after studying them carefully, made his choice. Kepler was probably the founder of our present elaborate card index system.

This epoch marked by Kepler and Galileo is certainly a noted one in the development of astronomy. While Kepler was discovering his beautiful laws of planetary motion, Galileo in Italy was doing work which in itself was epochal. When he applied the telescope to the skies for the first time a vast new field of investigation was started. This is so evident that we shall not dwell upon it further. In addition to this, however, he made several other contributions to science which would have made him famous, an account of which would require several lectures. We shall dwell only upon two. One of these is his support of the Copernican heliocentric theory which he upheld in his famous work entitled "*The Dialogue of the Two Systems.*" It was this support of Galileo that undoubtedly hastened its general acceptance.

I wish to dwell upon the second of these contributions more at length, as it marks one of the greatest epochs in the development, not only of astronomy, but in the whole realm of thought. It concerns that movement at the end of the Dark Ages known as the Revival of Learning, or Renaissance. This probably began in the 15th century, but, in my opinion, the rapid revival (so rapid, indeed, as to make it practically the Revival itself) began with Galileo.

As mentioned before, the dicta of Aristotle had held sway over the world's thought for some fifteen centuries. Among other things he had said that a large heavy body would fall faster than a small light body. Galileo, true scientist as he was, would not take the word of anyone, even Aristotle, for a thing when it was in his power to prove or disprove the statement. So mounting to the top of the Leaning Tower of Pisa, before a large gathering of interested people, he let fall from this height simultaneously two bodies, one large and heavy, the other small and light. According to Aristotle the heavy body ought to have reached the ground much sooner than the light one. But the astonished people saw the two falling side by side, and landing at the base of the Tower at practically the same instant. This was one of the most dramatic experiments the world has known. With the fall of those bodies fell the influence of Aristotle in matters scientific. You can easily imagine that, with the disproving of one of his dicta, the others immediately came into question. Investigators in all lines of thought soon began to appear, and the rapid revival of learning was on.

Galileo died in 1642, and Newton was born in 1643. The interval between Galileo's death and the epoch marked by Newton's activities was one of steady progress. Instruments were improved somewhat, and came into more general use; the micrometer was invented; accurate measurements of lengths of arcs in different latitudes were made from which it was found that the Earth is not a perfect sphere, but an oblate spheroid. Observational work was carried on most assiduously especially at the Paris Observatory. In addition to the discovery of the true form of the Earth, the most important developments at this time were the discovery of the finite velocity of light by Römer working under Cassini at the Paris Observatory, and Cassini's evaluation of the distance from the Sun to the Earth. He deduced the value $9''.5$ for the parallax of the Sun, which corresponds to a distance of 78,000,000 miles. This is the first good approximation to that all-important distance.

The next great epoch in the development of astronomy is that connected with the name of Sir Isaac Newton, who lived from 1643 to 1727. The work of this man, whose name is undoubtedly the greatest in astronomy, is so wonderful both in quantity and quality that it is difficult to know what to say about it in the few minutes available.

The name of Newton suggests immediately his law of Universal Gravitation, viz.: that every particle in the universe attracts every other particle in the universe with a force that is proportional to the product of the masses of the two particles and inversely proportional to the square of the distance between them. It would unfortunately take too much time to tell how he came to arrive at this law. This is the law upon which all work in theoretical astronomy and celestial mechanics is based. Newton is properly called the "Father of Gravitational Astronomy."

Kepler had shown in his three laws the manner in which the planets move, but he had not the slightest idea of *why* they move in this way. For some time a vague idea was prevalent that there was some such thing as a gravitational force residing in the Sun, but it remained for Newton to formulate it and prove it. Starting with his law Newton, with his mathematical genius, was able to prove Kepler's Laws and to show that, acting under the gravitational influence of the Sun in this way, they *must* move as described by Kepler. To do this and to prove other problems in theoretical astronomy the necessary mathematics were not available in Newton's time, so he had first of all to bring his marvellous mathematical talents into play. As a result of this he invented that all-powerful mathematical tool known as calculus. (The honor of inventing calculus has to be shared perhaps with the German mathematician, Leibnitz.)

With these and other mathematical tools which his sagacity gave us he was now able to explain many things which were awaiting explanation, among which may be mentioned the precession of the equinoxes, discovered by Hipparchus nearly twenty centuries previously; certain inequalities in the motion of the Moon; perturbations in general, and the tides. Another field of investigation was thus opened up which was quite as vast as that started by Galileo.

In addition to founding gravitational astronomy Newton may also be credited with the founding of modern astronomy or astrophysics when he discovered the composite character of white light, the phenomenon by which white light, when passed thru a prism, is broken up into its constituent parts and spread out into a band of color which we call the spectrum. Altho spectrum analysis did not begin to develop until the middle of the 19th century, its foundation was laid by Newton.

With this discovery of the composite character of light Newton was enabled to give the correct explanation of the phenomenon known as chromatic aberration, that trouble which the astronomers of that time were having with the fringe of color around an image which affected the sharpness of the image. Here Newton made a mistake in his scientific work, for he decided that this trouble could not be overcome. We now know how to eliminate chromatic aberration almost completely by making the object glass not of a single lens, but of two or more lenses of different density. But this discovery was made half a century after the time of Newton. We should be very thankful, however, that he made this mistake, for it led him to the invention of the reflecting telescope. Whereas the amount of bending of a ray of light upon passing thru a prism or lens depends upon its color, all rays, no matter what the color, obey the same law of reflection, viz.: that the angle of incidence is equal to the angle of reflection. Newton, therefore, saw that if the rays were brought to a focus on the principle of reflection, the image would be freed from chromatic aberration, as all of the rays, regardless of color, would be brought to the same focus, and a white object would yield a white image with no halo of colors to bother. Acting upon this idea he constructed the first reflecting telescope, a modest affair with a one-inch mirror made of a combination of copper and tin and highly polished. This instrument of such historical interest is still to be seen as one of the priceless exhibits in the library of the Royal Society in London. Altho small and inefficient this little instrument is the forerunner of the increasingly large and valuable reflectors culminating in our own time in the monster 100-inch reflector about to be put into operation at the Mount Wilson Solar Observatory.

The results of most of the work of Sir Isaac Newton were given to the world in the publication of his *Principia*, issued in three large volumes.

Beginning with the time of Newton we find astronomy developing so rapidly that its progress must now be traced, not as a whole, but along its various branches.

Just before the time of Newton the principal observational work had been done by the continental astronomers. One would naturally expect the next advances in the observational line to be developed by them and the theoretical branch to be explored by the English following Newton. But, curiously, the converse was the case.

During the 18th century the principal observational advances were made by the English. Toward the close of the 17th century Flamsteed, the first Astronomer Royal, founded the observatory at Greenwich. On account of the lack of funds his instrumental equipment was very meager and he did little beyond making a star catalog. The next two Astronomers Royal, Halley and Bradley, however, did much to advance the science.

Halley was a great admirer of Newton. Following some of the lines of Newton's work he computed the paths of some twenty-four comets. Noting that three of these were travelling in practically the same path, separated from each other at nearly equal intervals of 75 or 76 years, Halley ventured the idea that these were not three separate comets but were three appearances of one and the same comet at about 75 year intervals. He predicted the return of the comet. He did not live until the predicted year, but the comet appeared on schedule. This is the first instance of this kind in history, and the comet is named, as you know, Halley's Comet, in honor of the man who first predicted its return. The return which he announced took place in 1759. It has returned again twice since then, in 1835 and in 1910. This marked another advance in astronomy in that it added other moving bodies to the solar system, and showed the people that comets were no longer to be feared, that they were merely members of the solar system, moving under the attraction of the Sun, and that their motions and positions could be computed in accordance with Newton's and Kepler's Laws just the same as in the case of the planets.

Among other things done by Halley of a largely developing character may be mentioned his discovery of the proper motions of the stars; and his scheme for determining the solar parallax, and hence the distance from the Sun to the Earth, by observations of the transit of *Venus*.

Bradley, the successor of Halley, discovered aberration and nutation. All of the objects in the sky are displaced somewhat due to the facts that the Earth is moving and that the velocity of light is not infinite. This displacement is known as aberration. It was discovered by Bradley quite by accident in seeking to find a displacement of the stars due to parallax.

We must credit Bradley also with improving the accuracy of observational work. Not only was he a keen observer, but he had his instruments constructed by the most skillful mechanics and mounted in the best possible manner. Further, he was one of the first to take into account possible errors arising from defects of his instruments.

Contrary to natural expectation we find but little done in the 18th century in England along the lines of Gravitational Astronomy. This country does not seem to have possessed minds of a caliber to follow the lead of the immortal Newton. His work was principally geometrical and for this reason difficult to master. On the continent, however, there appeared a group of mathematical astronomers who founded and developed what is called the method of *analysis*, that is, a development following the lines of algebra. With this they were enabled to develop the planetary and lunar theories of celestial mechanics to a very high state. The leaders in this work were Euler, a Swiss, Clairaut, D'Alembert, Lagrange, and Laplace of the French school. Lack of time prevents a detailed statement of what they accomplished. The state of the developments at this time is published in the monumental work of Laplace entitled the *Mécanique Céleste.* Among the interesting and important things done by Laplace may be mentioned his proof of the stability of the solar system, and of the fact that *Saturn's* rings could not be solid. The physical proof of the latter was not accomplished until near the end of the 19th century, when it was beautifully demonstrated by Keeler.

Laplace also set forth in a beautiful work, the *Systême du Monde,* the Nebular Hypothesis that goes under his name. This theory of the formation of the solar system held sway for more than a century.

During the latter part of the 18th century and the first part of the 19th observational astronomy was carried to great heights by Sir William Herschel working with his devoted sister Caroline at Slough, England. His remarkable work was made possible by the large instruments, reflectors, that he made, culminating in his forty-foot telescope.

He added the knowledge of the existence of planet *Uranus* by discovering it accidentally in 1781. He made many other observational discoveries, but his most important development work was his discovery of binary star systems and his general survey of the sky for nebulae and the distribution of the stars. These led him to speculate on the form of the sidereal universe and mark the beginning of that wonderful work that is the principal problem of the 20th century astronomers. His investigations led him to set forth his so-called "grindstone theory," that is, that the universe is shaped like a grindstone having the greatest depth in the plane of the Milky Way.

The developments in the 19th century were so numerous as to become almost bewildering when one trys to narrate them. We can at best mention here but few. Gravitational astronomy has been improved and developed along the lines laid down by the five famous mathematicians of the 18th century, in large part by Pontécoulant, Delaunay, Leverrier, Poincaré, Gauss, Hansen, Gyldén, Adams, and our own Newcomb and Hill. Time does not permit of the enumeration of the individual contributions of these and yet others. But I will pause to mention two things. The first is the discovery of *Neptune* in 1846 which resulted from the computational work of Adams, of England, and Leverrier, of France. The other is that the best lunar theory we have is that given us by the famous American, G. W. Hill, to whom the Bruce Medal of the Astronomical Society of the Pacific was awarded shortly before his death a few years ago.

Observational astronomy progressed with rapid strides in the last century, due to the improvements in the size, number, and quality of instruments, and in the mathematical methods deduced for handling observational material. The latter are due principally to Gauss and Bessel. We owe to Bessel also the first detection of the parallax of a star. Instruments were made much larger and better, principally here in America, culminating toward the end of the century in the great refractors of the Lick and the Yerkes Observatories.

Toward the end of the century two important discoveries were made which must be mentioned. The first is the discovery of the variation of latitude by Küstner at Bonn; the other is the discovery made by Keeler at the Lick Observatory that the spiral nebula is the rule and not the exception among the nebulae. The latter gave the final blow to knock the props from under the tottering Nebular Hypothesis of Laplace and started the astronomers again to thinking upon the structure of the universe.

Finally, in this hurried review, we come to note the development of modern astronomy or astrophysics. This was started, as was related, when Sir Isaac Newton discovered the composite character of light. Early in the 19th century Fraunhofer had noted and mapped certain dark lines running across the spectrum of the Sun, the lines which are named after him. The true explanation of these was given about the middle of the century by Kirchhoff, and the new science of astrophysics was well started. Here again was opened up a new field of investigation quite as large as that started by Galileo with his telescope.

In this, the 20th century, the reflecting telescope is outstripping the refractor. We have ever larger and larger reflectors, culminating, as has been told, in the 100-inch reflector at Mount Wilson. Hand in hand with this goes the development of spectroscopes and minor apparatus, and the perfection of photographic processes. Keeler's discovery concerning the nebular forms, and the development of astrophysics mark an epoch which starts the 20th century well on its way to master the great unsolved problem of astronomy, the structure of the universe.

I am only too well aware of how inadequate this sketch is; many more things perhaps should have been said. I hope, however, that, incomplete as it is, this account has given you some idea of the various foundation stones upon which the beautiful astronomical superstructure has been erected.